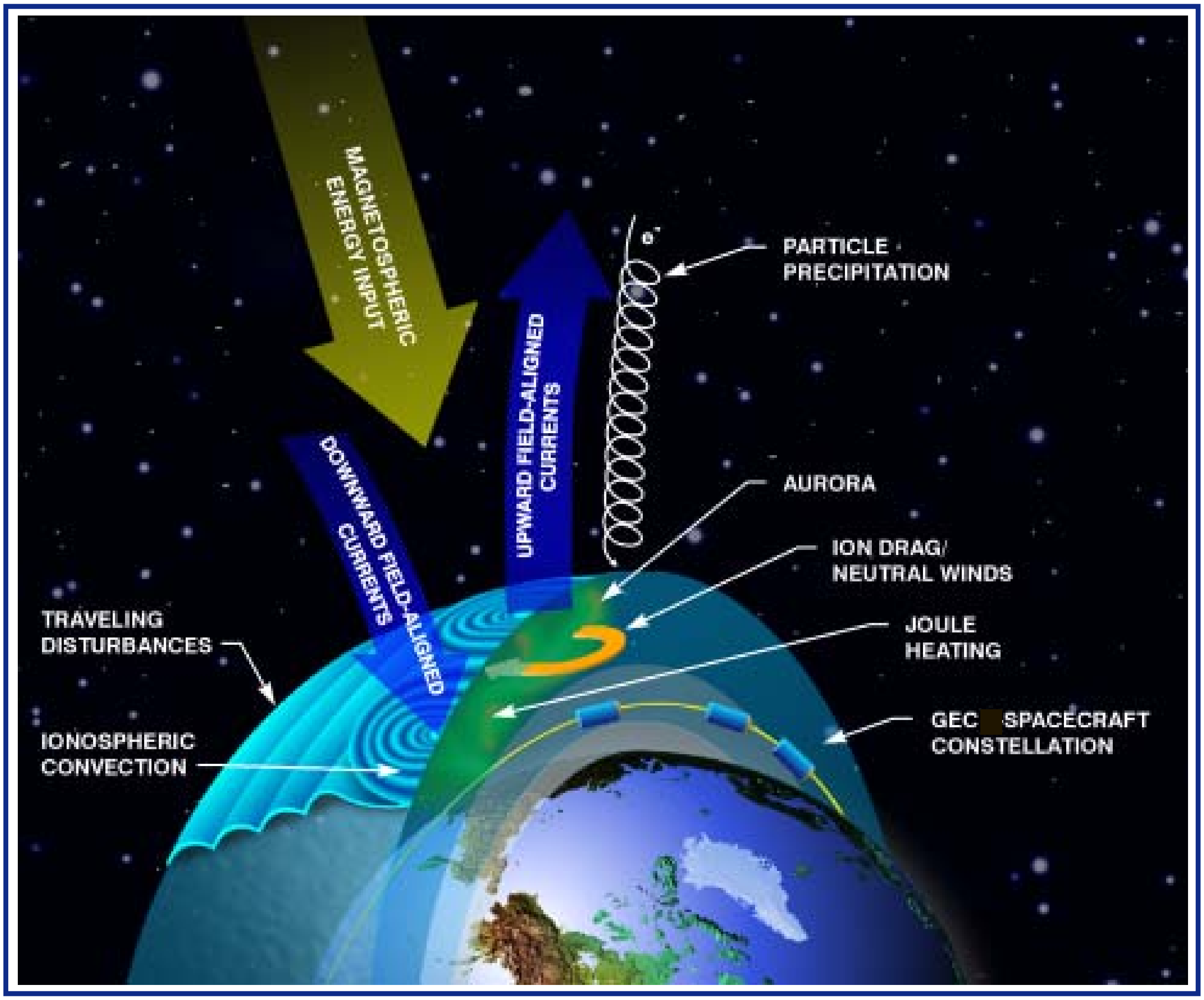
GEC: A Mission to the Threshold of Space

Updated Overview of the
report of the NASA science and technology definition team
for the
geospace electrodynamic connections mission



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GEC: A Mission to the Threshold of Space

The Geospace Electrodynamics Connections (GEC) Mission will provide the first comprehensive, direct measurements of the threshold region of Earth's atmosphere and its contact with space: GEC will tell us how the threshold of our high-latitude atmosphere interacts with, responds to, and mediates externally imposed energy and momentum.

At the very edge of Earth's atmosphere lies a region that marks the transition from the neutral atmosphere to the plasma state of space. In this threshold region, both neutral and charged gases coexist, interact, and respond to the magnetic and electric fields and energetic particles of space. This region is an electrically charged planetary boundary layer that constitutes the innermost layer of the ionosphere–thermosphere (I–T) system. This I–T boundary layer acts as a depository of energy from distant sources, an intermediary for charged and neutral gases, and a regulator of electrical coupling with the magnetosphere. The I–T boundary layer is a crucial element in the electrical connections that occur between the Sun and Earth. However, despite the nearness of this layer, it is one of the least directly measured regions of our geospace environment. The GEC Mission will explore the role of this contact layer in the coupling between the overlying space environment and our planet's atmosphere.

The physical processes that characterize the I–T boundary layer are dominated by interdependent interactions of the ionized and neutral gases and by distant source regions that are coupled via Earth's magnetic field. Significant energy is transferred into this region by the charged particles, electric fields, and electric currents of the high-altitude magnetosphere as well as by upward-propagating tides and waves from the lower atmosphere. The I–T boundary layer generates an upward feedback into the magnetosphere and modulates influences of the space environment on the lower regions. Resolving these processes in our own I–T boundary layer is the heart of the GEC mission.

Mars and Venus, the most Earthlike planets in the solar system, have a contact region like Earth's except for one very important difference: neither of these planets has a large intrinsic magnetic field. As part of this mission, we will gain an improved understanding of how great a role Earth's magnetic field plays in the evolution and stability of life

***Cover Photo:** Processes that characterize the Ionosphere–Thermosphere boundary layer coupling of Earth's space environment to our planet's atmosphere at high latitudes.*

on the planet's surface. Understanding the contact of our geospace environment and the atmosphere is a necessary part of providing closure to the connections between the Sun and our planet.

To accomplish the goals of the GEC mission, in situ measurements of the neutral and plasma properties within the contact region are required. As such, a "deep-dipping" element of the mission is imperative to reach the regions where fundamental interactions connect the atmosphere and space. Because the response and scale dependencies of the neutral and plasma gases are vastly different, a multispacecraft mission is needed to quantify the persistence of the energy inputs and the response of the contact region. In this report, we outline a cost-effective, reconfigurable constellation of small satellites that will resolve these key issues.

This document provides a brief, updated overview of the Science and Technology Definition Team (STDT) report for GEC (the original report is available at *http://stp.gsfc.nasa.gov/missions/gec/)*. Our purpose is to more clearly identify the key focus of the mission and to establish science priorities by which the anticipated productivity of the mission can be evaluated. GEC will make a unique contribution to the Sun–Earth Connection theme by exploring this region where the ions in the atmosphere transition from being strongly influenced by collisions to being dominated by the ambient electric and magnetic fields. Specifically, GEC will discover how geospace energy is coupled into the atmosphere.

Science Priorities

Science priorities for the mission have been established by noting that the full effects of collisions between the ion and neutral gases must first be understood. Then, the relationships between different scales in the ion and neutral gases can be assessed, leading finally to an ability to uncover how the many different scales evolve and interact in time. Accordingly, the GEC scientific priorities can be clearly set; these are described below in priority order:

1. Ion-neutral collisional interactions

Key Question: *How do the collisionally coupled charged and neutral atmospheric constituents in the IT boundary layer respond to electrodynamic input imposed from space?*

The electrodynamic connection of Earth's atmosphere to space is determined by the collisional interaction of the charged gases of the lower ionosphere and neutral gases of the lower thermosphere. Within this Ionosphere–Thermosphere region, energy and momentum are exchanged between the ionized gas and the neutral gas through mechanisms such as Joule heating and direct momentum transfer. The magnitudes and partitioning of energy and momentum transfer in the interaction depend on the detailed multiple-scale physical parameters that can be determined only through direct in situ observations. Spatial scales, temporal scales, and correlations among the fields, and the ion and neutral parameters, all contribute to determining the response to the electrodynamic input. Joule heating alters the temperature and pressure of the neutral gas, inducing strong vertical motions that modify the composition and couple to the global circulation. Momentum transfer modifies the ion-neutral velocity difference, which in turn modifies the electrical currents and the heating rates. While we know much about these interactions from previous missions at higher altitudes (>300km), there remains much that we do not know, particularly at the lower altitudes (<200 km), where Joule heating and momentum transfer effects are strongest.

Among the least well-known, yet most critical, factors that control the I–T interaction is the ion-neutral collision frequency. The absolute magnitude of heating and momentum transfer rates depends critically on this parameter, as does the electrical conductivity of the region. Without in situ measurements of the various electrodynamic parameters in the altitude region where the collision frequency significantly affects the observations, it can be inferred only from theory using estimates of the atmospheric composition and density. Such estimates rely on laboratory measurements and theoretical calculations to determine the collision cross-sections, which are obtained under pressures and temperatures for which their relevance to I–T conditions entails considerable uncertainty. Hence, a critical element of the GEC mission includes repeated excursions to low altitudes (<200 km), where the appropriate measurements can be obtained directly.

Currently, our knowledge of the magnitude and scale size of the dynamic interaction below 200 km altitude is insufficient to describe the response of the system to the complex electric fields and particle precipitation imposed on our upper atmosphere. To close this knowledge gap, GEC must:

- Measure the ion and neutral velocities, **E×B** velocity, and neutral composition and density, over an altitude region where the difference between the **E×B** velocity and the ion drift velocity can be determined.
- Measure the electric field, energetic particle distribution, and currents to specify the input drivers and their spatial structure.
- Use measurements of ion and neutral particle dynamics, composition, and density to determine the ion-neutral collision frequency.
- Measure the ion and neutral velocities to describe the neutral wind response to ion drag forcing and altered pressure gradients.
- Measure temperature, densities, and velocities of the neutral and ionized gases, including their relative compositions, to quantify the multiple-scale responses of circulation and composition to Joule heating.
- In an extended mission phase, assemble measurements from a petal orbit configuration to reveal vertical gradients in the electric currents and in the atmospheric responses.

2. Scales of electrodynamic drivers and responses

Key Question: *How are the spatial variations and persistence of the electrodynamic drivers related to the neutral responses?*

Spatial and temporal variations of the electrodynamic drivers incident on the I–T system can produce a wide range of responses that depend on the scales and persistence of those variations. For example, air can be accelerated toward the ion velocity only if the ion-drag forcing is persistent, and if the forcing region is large enough that air parcels remain within it for an extended period. The relevant timescale is determined by the effectiveness of the neutral-ion collisions, which varies from many hours to a fraction of an hour, depending on the ion density. The relevant spatial scale is, basically, this timescale multiplied by the wind velocity. Since Joule heating is proportional to the square of the ion-neutral velocity difference, the magnitude of Joule heating is reduced when the wind velocity approaches the ion velocity. Vertical neutral velocities respond within minutes to changes in the local Joule heating. Acoustic-gravity waves are generated on a wide range of temporal and spatial scales. Global circulation responds within a few hours to changes in the large-scale Joule heating. Localized electric fields can interact in a significantly different way with the air than larger scale fields, as the former are more likely to produce plasma instabilities and irregularities, as well as intense vertical winds that may cause mixing of air parcels over a greater vertical extent. All of these responses are strongly dependent on altitude. Our current ability to address these spatially and temporally varying inputs and responses is severely limited by an inadequate knowledge of the significant spatial and temporal scales. Parameterizations in models are also based upon an inadequate knowledge. To close this knowledge gap, GEC must:

- Use multiple satellites configured with "pearls on a string" separations along the same orbit path to resolve space and time variations of the electrodynamics drivers and the local neutral and ionized gas response properties.
- Determine the persistence and correlation of the inputs and responses by obtaining the measurements with temporal spacings between at least two satellites ranging from 10 seconds to 30 minutes.
- Measure the electric field energetic particle flux and plasma density with a sample rate that allows resolving static structures with scale sizes of 1 km and greater.
- Measure the **E×B**, ion, and neutral velocities with a resolution of 1 km over an altitude region where the difference between the ion drift direction and the **E×B** direction can be determined.

3. Evolution and feedback

Key Question: *How, and under what conditions, do the responses evolve and feed back on the drivers?*

Electrodynamic inputs to the system produce responses in the neutral and ionized gasses that differ in both spatial and temporal scales because of the greater influence of inertia and viscosity in the neutral gas. The neutral response may extend well beyond the period and spatial region over which the input is delivered. Inertia in the neutral atmosphere can maintain an imprint of the input that is conveyed back to the ionized gas via a flywheel effect. Thus, while currents may be driven in the region from outside influences, they are modified by the response of the system. By modifying the current in the magnetosphere–ionosphere–thermosphere (M–I–T) circuit, the altered I–T system will feed back on the magnetospheric driver. Currently, we have very little information on these influences and how they evolve. Understanding them, however, is critical to understanding the interaction between the atmosphere and the geospace environment. To rise to this challenge, GEC must:

- Measure electric and magnetic fields to identify the direction of electromagnetic energy flow, which is downward for magnetospheric input and upward when driven from below by the flywheel effect.

- Measure the neutral wind, ion drift, electric fields, and plasma density in situ with temporal separations from 10 seconds to 30 minutes between at least three satellites to characterize the evolving properties of the ionospheric portion of the M–I–T circuit.
- Correlate the rate of change of the electric field, energetic particles, and currents with changes in the ion and neutral drifts and gas properties including composition to expose the influence of feedback from the atmosphere.

Implementation

From missions such as Atmosphere Explorer, which made very limited excursions to low altitudes with low-duty-cycle, low-data-rate instruments, and TIMED, which measures some important signatures of the lower I–T region via remote sensing, we know that, in order to understand the interaction of the neutral and ionized gases as well as the impacts of the temporally varying inputs, we must sample this region directly. The GEC spacecraft must, therefore, have the capability to dip to low altitudes into the region where collisional effects are dominant. A deviation of the ion drift from the $\mathbf{E}\times\mathbf{B}$ drift is a key indicator that must be detected with high fidelity. It will be necessary to measure not only below 150 km, but also at a range of altitudes above 150 km, because the collisional effects vary strongly with height. In fact, data from GEC's "parking perigee" of 200–250 km will provide a wealth of information about ion-neutral interactions and their effects in a region that has hitherto been only sparsely sampled. However, measurements at 200–250 km alone will not be able to answer the primary science questions of GEC.

The GEC mission must also consist of two or more spacecraft strung out primarily along a common orbit, in a pearls-on-a-string manner, or sometimes vertically aligned in a petal orbital configuration as they carry out their low-altitude passes to discover and specify the spatial and temporal variations in the region. The number of satellites required to gather the necessary data to successfully address each GEC science question varies in accordance with each question. Significant progress on the first GEC science question concerning understanding the basic ion-neutral collisions can be achieved with one satellite. Two satellites are needed to significantly advance our understanding of the second GEC science question, concerning electrodynamic scales and responses. The third GEC science question, to understand the evolution of the lower I–T system and its feedback on the magnetosphere, requires three satellites. This is summarized in Table 1.

Table 1. GEC—Science Drivers for the Multiple Satellite Approach

Science Question	Minimum number of satellites to ensure comprehensive progress
1. Ion-neutral collision interactions	1
2. Scales of electrodynamics drivers and response	2
3. Evolution and feedback	3

In order to put the GEC data in context as well as define the I–T boundary layer background parameters, GEC observations should be gathered in conjunction with dedicated campaigns in coordination with ground-based facilities, such as incoherent scatter radars and all-sky cameras. Theoretical and empirical modeling will also be an integral part of the mission strategy.

The data returned by the GEC spacecraft and by the complementary ground-based instruments will be highly detailed and complex. Their interpretation will require advanced models with the ability to simulate the multiscale interacting ion-neutral processes over domains that range from hundreds of kilometers to the entire globe. The unprecedented data will constrain and test the models in ways not previously achievable. In return, successful simulations will provide a continuous space–time picture of the measured parameters, and will enable detailed analyses of the physical processes that are operating. The data will also contribute significantly to empirical models that, among other things, provide inputs and parameterizations for the global simulation models.

Measurement Goals

Table 2 summarizes the key mission measurements needed to accomplish the GEC science objectives. For each geophysical parameter, the range is dictated by its expected geophysical variability. This variability results from the need to sample over all local time regions and over an altitude region where the ion-neutral coupling varies considerably. The accuracy is dictated by the magnitude of changes associated with the magnetospheric drivers and the I–T system response. For example, to measure changes in the field-aligned currents will require a sensitivity in the measurement of magnetic field perturbations of 10 nT. Changes in vertical neutral winds resulting from localized Joule heating will require a sensitivity of 5 m/s. It should be emphasized that the GEC mission encompasses two phases of an investigation: one of discovery and another of quantification. Table 2 describes measurement goals in rather general terms without discussion of the measurement techniques or the needs that are specific to a given investigation. The SDT believes that the discovery phase

Table 2. GEC "Nominal" Mission Below 500 km—Critical Science Measurements

	Science Questions			Measurement Requirements		
Science Parameter	Q1. Collisions, Ion-Neutral Coupling	Q2. Temporal/ Spatial Scales	Q3. Evolution and Response	Range	Accuracy	Temporal Resolution
Electric Fields (vector)	H	H	H	0–300 mV/m	0.25 mV/m	0.1 sec
Ion Velocity (vector)	H	H	H	0–6 km/s	5 m/s	0.1 sec
Neutral Velocity (vector)	H	H	H	0–2 km/s	5 m/s	1 sec
Magnetic Field (vector)*	H	H	H	0–65000 nT	10 nT	0.1 sec
Energetic Electron Fluxes 0–20 eV (all angles, 20° res.)**	M	M	M	10^8–10^{12} eV/cm^2/s/sr/eV	15% fluxes, 15% energy	1.1 sec
20 eV–30 keV (all pitch angle, 20° res.)	H	H	H	10^6–10^{10} eV/cm^2/s/sr/eV	15% fluxes, 15% energy	1.1 sec
30 keV–300 keV (downward flux, 90° res.)	L	M	H	10^4–10^8 eV/cm^2/s/sr/eV	20% fluxes, 25% energy	1 sec
Energetic Ion Fluxes 20 eV–20 keV (all pitch angles, 20° res.)	M	M	M	10^5–10^9 eV/cm^2/s/sr/eV	15% fluxes, 15% energy	0.1 sec
20 keV–1MeV (downward flux, 90° res.)	L	M	H	10^3–10^7 eV/cm^2/s/sr/eV	20% fluxes, 25% energy	1 sec
Plasma Density	H	H	H	10^2–10^7 cm^{-3}	± 10%	1.1 sec
Ion & Electron Temperature	H	H	H	300–10000 ° K	± 10%	1 sec
Neutral Density	H	H	H	10^9–10^{12} cm^{-3}	± 10%	1 sec
Neutral Temperature	H	H	H	300–3000 ° K	± 10%	1 sec
Ion Composition (H^+, O^+, NO^+, $O2^+$, Mg^+, Fe^+)	H	H	H	relative concentration	± 1%	1 sec
Neutral Composition (O, N_2 O_2)	H	H	H	relative concentration	± 1%	1 sec

Importance: H = High, M = Moderate, L = Low

* Magnetic field measurements are needed to provide estimates of the local and remote measurements of currents (field-aligned, Pedersen, Hall) as well as Alfvén wave measurements and Poynting Flux computations. GEC is not primarily interested in measurements of Earth's ambient magnetic field.

** Suprathermal electron measurements would provide evidence of low-energy auroral fluxes, and if they had sufficient sensitivity, could provide local current measurements associated with low-energy electrons.

can be successful even with slightly relaxed measurement capabilities. It is expected that individual instrument proposals will demonstrate the need and capability to provide measurements required for specific investigation goals.

The measurement requirements have been discussed at the end of each science question section above. As can be seen in the table, a complete suite of electrodynamics, neutral gas, and plasma measurements are needed to address each question. Some of the particle measurements are not discussed explicitly in the science question narratives, but are needed for context to distinguish boundaries and for magnetospheric inputs. For example, the energetic ions are most useful to define the cusp and dayside aurora. The high-energy ions and electrons can be used to define the ring current trapping boundaries, and their offset will provide information concerning the drivers of subauroral ionospheric drifts. The suprathermal (0–20 eV) electron measurement would be valuable as both a detector of low-energy auroral fluxes and a potential direct measurement of currents. Note that this latter application has not yet been demonstrated, and it is not of crucial importance, given the expected measurements of current from magnetometer observations.

Orbit Requirements

Three arrangements of the satellite orbits are required to conduct the GEC mission: "deep dipping," pearls-on-a-string configuration of multiple satellites separated along the same orbit, and "petal orbits." These options and their science drivers are discussed in the original GEC STDT document. In brief, the pearls-on-a-string configuration allows GEC to sample a particular region in the sequence of one spacecraft followed by another (Figure 1). Separations between 1 and 30 minutes will allow temporal variations of these periods to be specified for features that have corresponding longitude coherence. This configuration is a powerful and necessary tool to discover the impact of features with different levels of persistence. Vertical coupling is most efficiently investigated by employing a petal configuration that provides for the satellites to simultaneously sample the same latitudinal region at different altitudes (Figure 2).

Guidance for prioritization of capabilities beyond minimum requirements, in order of scientific value

1. Increased depth of dipping with a goal to achieve routinely perigees of 130 km.
2. More coordination of campaigns with ground-based facilities.
3. Increased number of high-latitude campaigns (conducted at other local times).
4. Addition of "petal" campaigns.
5. Increased campaign durations.
6. Addition of low-latitude perigee campaigns (perigee below 150 km desired).
7. Addition of high-latitude campaigns needed to resample local times during different seasons.

Additionally, the requirement to make measurements at high latitude and many local times makes an orbital inclination of 83 degrees optimal.

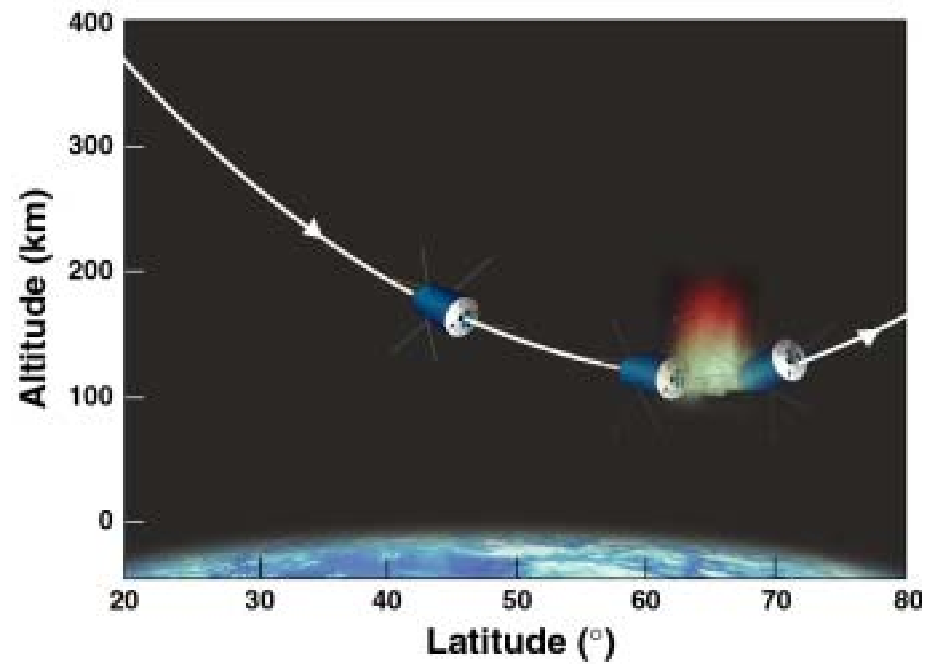

Figure 1. The pearls-on-a-string configuration.

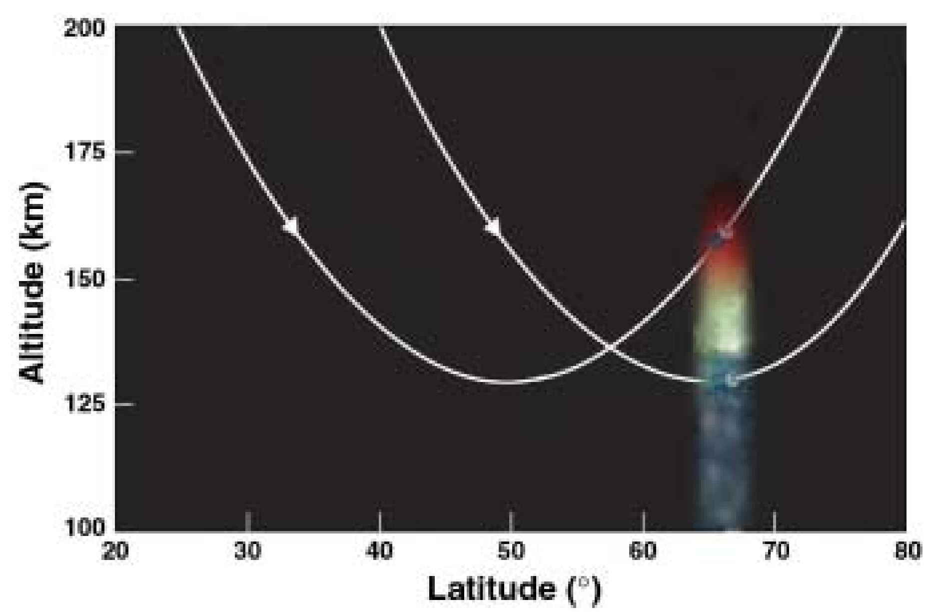

Figure 2. The "petal" formation for two of the GEC spacecraft.

Dipping Strategy

The possible approaches to dipping campaigns are many because of the flexibility inherent in the locations, durations, and amounts of perigee excursion. The trade space is large in terms of science return and resource expenditure, so guidelines for developing a dipping strategy are necessary. The basic approach follows from the science priorities above. Because the high-priority GEC science occurs at high latitudes, the dipping strategy must emphasize campaigns performed at high latitudes. The high-priority phenomena manifest themselves most profoundly below 150 km, so spending a significant amount of time below 150 km is a high priority. The phenomena are not uniformly distributed in local time, so measurements over a range of local time are necessary. Coordinated measurements with ground-based facilities are also a high priority. **These priorities lead to minimum dipping requirements of three 1-week, high-latitude campaigns having perigee less than 150 km. The campaigns must be well separated in local time, and at least one of the campaigns must be coordinated with a scientific radar facility such as Sondrestrom or the National Science Foundation's new Advanced Modular Incoherent Scatter Radar (AMISR).**

Mission Success Criteria

The centerpiece of the GEC mission is the ability to access the collision-dominated region of the I–T boundary during so-called "deep dipping" campaigns. This new in situ exploratory capability should not detract from the important information that will be obtained from the relatively low perigee of the baseline orbit and from the opportunity to examine the behavior of our atmosphere at much higher altitudes near apogee. In assessing the science goals set forth by the STDT, it is clear that the major impacts to the full achievement lie in the clarity with which the collisional effects can be described and in the ability to quantify the spatial and temporal scales that are important. This clarity will, in turn, depend upon the reproducibility of the phenomena that are discovered and, thus, on the number of opportunities to access the region and gather time-separated measurements within it.

There are four discrete levels of success for GEC: Full Science, Minimum Science, Partial Science 1, and Partial Science 2 (described at right). Each affects the science return for GEC objectives 1, 2, and 3 differently.

Table 3 summarizes the STDT's evaluation of GEC success.

Full Science Mission Achieved by a three-satellite configuration in which all instrument complements function successfully and as a constellation achieves at least 10 1-week-long, deep-dipping campaigns, with three of these centered on the northern auroral region as defined in the Minimum Science Mission. A petal orbit configuration established at high latitudes following the dipping campaigns will allow examination of altitude variations seen along a single set of orbits.

Minimum Science Mission Achieved if two satellites are able to complete three simultaneous deep-dipping campaigns. Each campaign would need to be 1 week long, with perigee in the 130–140 km range, with latitude of perigee being the Northern Hemisphere centered near 65° and in the local time sectors of noon, premidnight, and midnight. The spacing between the satellites should be in the 2- to 10-minute range. The seasonal constraint would be that either the premidnight or midnight sector be in winter.

Partial Science Mission 1 Defined as the scenario in which two GEC satellites successfully complete at least 10 deep-dipping campaigns as outlined in the Full Science Mission. Note that two satellites as described above have three possible interpretations: 1) GEC has only two satellites, 2) GEC dips only two satellites, or (3) only two GEC satellites have full operational capabilities.

Partial Science Mission 2 Defined as the scenario in which a full, three-satellite GEC mission is able to complete only three deep-dipping campaigns, but otherwise completes a 2-year mission.

Table 3. Relative Accomplishment of GEC Science Goals for Different Levels of Mission Performance

Mission	Science Q1	Science Q2	Science Q3
Full Science	100%	100%	100%
Partial 1	90%	60%	50%
Partial 2	70%	80%	70%
Minimum	60%	40%	40%

Contributions of GEC to SEC Systems Science

The multisatellite GEC science mission, with its comprehensive measurement suite and with altitudes extending above 1,000 km, also will address a large number of outstanding ionospheric physics problems that are beyond the focus of GEC and, hence, are not described in the GEC reports. Such secondary science constitutes an important element of the GEC mission and demonstrates the great utility of this unprecedented mission to NASA and the science community.

For example, the period since the STDT report was prepared has seen the launch of NASA's IMAGE and TIMED spacecraft, their exciting new results, and the flowering of the so-called system science approach to understanding the physics of the Sun–Earth System. The new results from TIMED and IMAGE have refocused our attention on poorly understood phenomena occurring in and above the F region ionosphere, such as Sub-Auroral Polarization Streams (SAPS) and large-scale plasmaspheric dynamics. The instrumentation required to meet the GEC science goals will also return data from the F region and above that will resolve spatial/temporal ambiguities that have limited our understanding of these and other high-altitude ionospheric phenomena.

The systems approach to SEC science has clearly demonstrated the value of using a fleet of operating satellites, originally launched for diverse purposes, to address the flow of mass and energy through the Sun–Earth system. These system studies are the focus of NASA's Living With a Star program. Several new missions, such as NASA's Magnetosphere Multiscale Mission, the LWS Ionospheric Storm Probes, and proposed International LWS missions, such as Canada's EPOP (polar wind) mission, are anticipated. If GEC is propitiously launched, it could contribute significantly to the systems science from such a fleet of simultaneous geospace observatories.

Authors

GEC Science Definition Team Members

Co-Chair
J.J. Sojka
Utah State University

Co-Chair
R.A. Heelis
University of Texas at Dallas

W.A. Bristow
University of Alaska, Fairbanks

J.H. Clemmons
Aerospace Corporation

G. Crowley
Southwest Research Institute

J.C. Foster
MIT Haystack Observatory

C. Kletzing
University of Iowa

L.J. Paxton
Applied Physics Laboratory

W.K. Peterson
NASA Headquarters/LASP

R.F. Pfaff
Goddard Space Flight Center

J.P. Thayer
Stanford Research Institute

A.D. Richmond
National Center for Atmospheric Research

GEC Project Scientist

J.M. Grebowsky
Goddard Space Flight Center